Pergamon

Space Technol. Vol. 17, No. 3-4, pp. 195–203, 1997

Printed in Great Britain
0892-9270/98 $19.00 + 0.00

PII: S0892-9270(97)00037-7

MICROSENSORS AND MICROINSTRUMENTS FOR SPACE SCIENCE AND EXPLORATION

C. A. KUKKONEN[1] and S. VENNERI[2]

[1]Center for Space Microelectronics Technology, Jet Propulsion Laboratory, 4800 Oak Drive, Pasadena, CA 91109, U.S.A. and [2]National Aeronautics and Space Administration, Code AF, Washington, DC 20546-0001, U.S.A.

Abstract—Most future NASA spacecraft will be small, low cost, highly integrated vehicles using advanced technology. This will also be true of planetary rovers. In order to maintain a high scientific value to these missions, the instruments, sensors and subsystems must be dramatically miniaturized without compromising their measurement capabilities. A rover must be designed to deliver its science package. In fact, the rover should be considered as the arms, legs and/or wheels that are needed to enable a mobile integrated scientific payload.

miniaturization

INTRODUCTION

In the past, most planetary exploration missions have been flybys or orbiters that conducted remote sensing of planets, comets and asteroids. Many future missions will land on the surface and make *in-situ* measurements of physical, chemical and biological properties of these objects. These measurements require miniature field geology equipment, chemical and physical analysis facilities, micro-weather stations and capability for biochemical analysis. Likely scenarios for exploration will limit the entire payload mass to a few or possibly a few tens of kilograms (Fig. 1).

In order to sample over a larger area of the surface or to obtain global coverage, new approaches will be used. A single mission might seed the surface with dozens of micro-landers or penetrators for global weather or seismic information or to obtain a representative analysis of the soil composition (Fig. 2). If the body has an atmosphere a robotic balloon (aerobot) may be used to move a science package from place to place. Starting from a fixed landing site, a rover can carry an instrument package for extended and detailed exploration of the surface.

The total mass of future microlanders, penetrators, or microrovers will be very limited with many less than 2 or 3 kg. With these constraints, it will not be possible to design a general purpose vehicle to which instruments can be bolted. The vehicle must be tailored to, and integrated with, the science package it is intended to deliver. There needs to be one integrated structure, one thermal control system and one computer. To the maximum extent possible, the science imaging system should be integrated with the vehicle imager. The vehicle is a sciencecraft and the rover becomes wheels attached to the integrated science instrument.

This is not how things are done today. Current rovers are designed as an independent multipurpose vehicle with some volume, mass, electrical power and telemetry available for a payload. Potential scientific payloads are limited to those that can fit within the envelope of the rover capabilities. A payload may be rejected because it does not fit within this envelope or because it requires a special capability like a robotic arm or drill.

The development of an integrated miniature mobile science laboratory will require interdisciplinary team of engineers and scientists. It will also require a new approach to selecting scientific investigations. A competition will be held amongst various interdisciplinary teams each consisting of several scientists and their mobility and sample acquisition engineering colleagues. The space science community has some recent experience in this area responding to NASA's solicitation for integrated science payloads for Mars 1998 and 2001. Now the engineers will have to be brought into the process.

The ability to carry out meaningful science within severe mass, volume and power constraints requires considerable innovation in miniature instrumentation. Many of the measurements needed on the surface of Mars are currently done in laboratories on Earth using a large conventional apparatus. A terrestrial chemical or physical analysis laboratory occupies an entire room. The challenge in space is to selectively target the most important measurements and then either miniaturize the conventional instrument or develop a new way to make the measurement.

Miniaturization, in most cases, is much more difficult than straightforward engineering. One has to examine the fundamental measurement principles and understand why the current instrument is large. The factors may include the need for a large optical

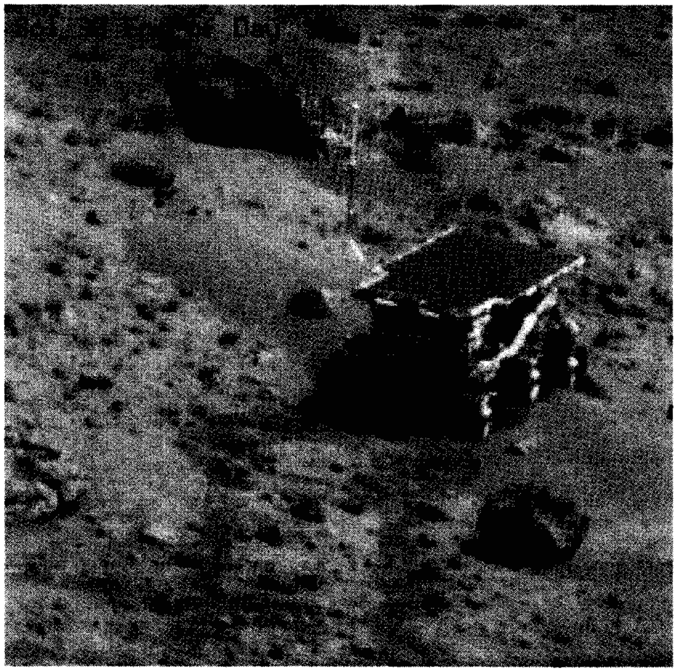


Fig. 1. Mars “Sojourner”. The 12 kg rover landed and began exploration of Mars on July 4, 1997.

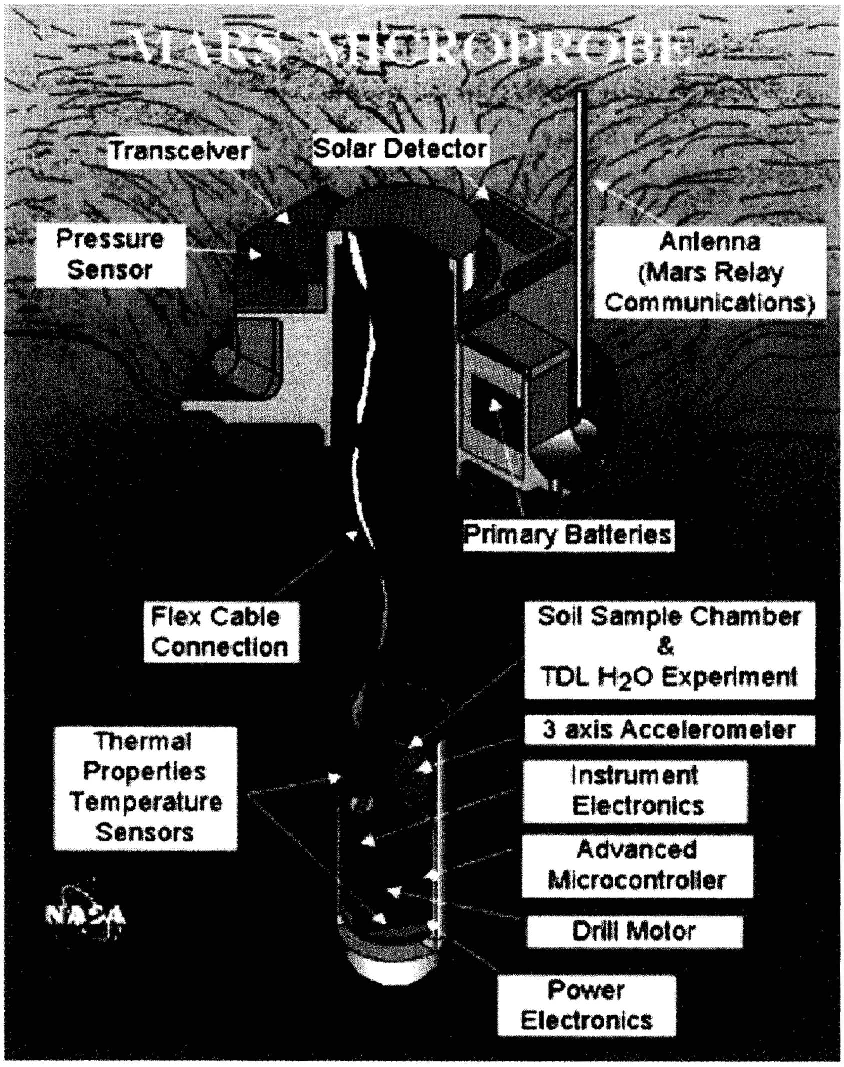


Fig. 2. Deep space-2 Mars microprobe. Two 2 kg microprobes will be carried as demonstration experiments on the Mars 1998 lander mission.

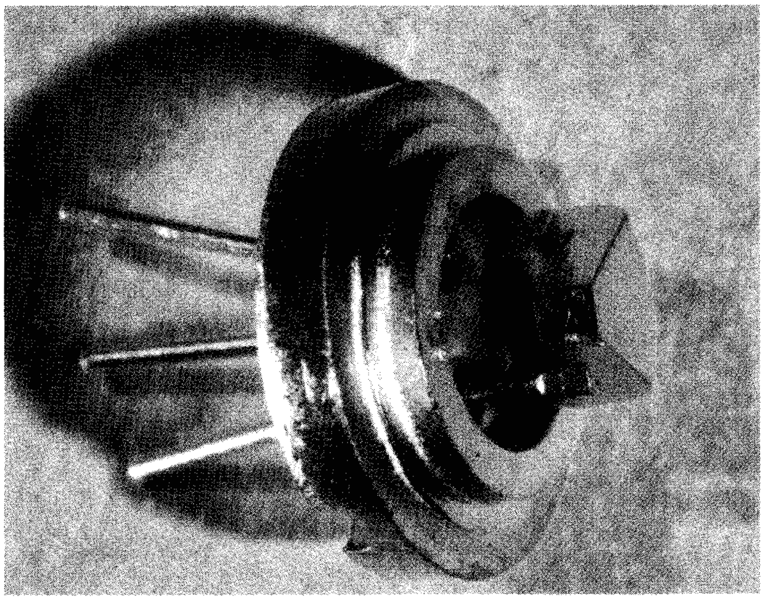


Fig. 3. An uncooled tunable diode laser packaged for instrument use. The diode laser is the black chip the size of a pencil point mounted to the brass heat sink.

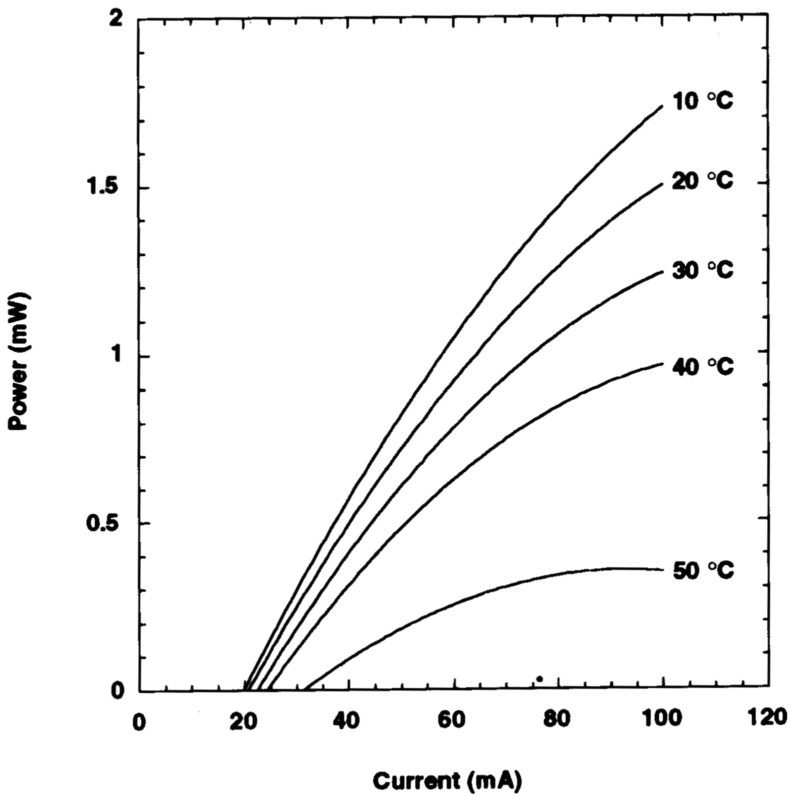


Fig. 4. Continuous light output versus current between 10 and 40°C for a single-mode distributed feedback laser at ~2.0 μm wavelength.

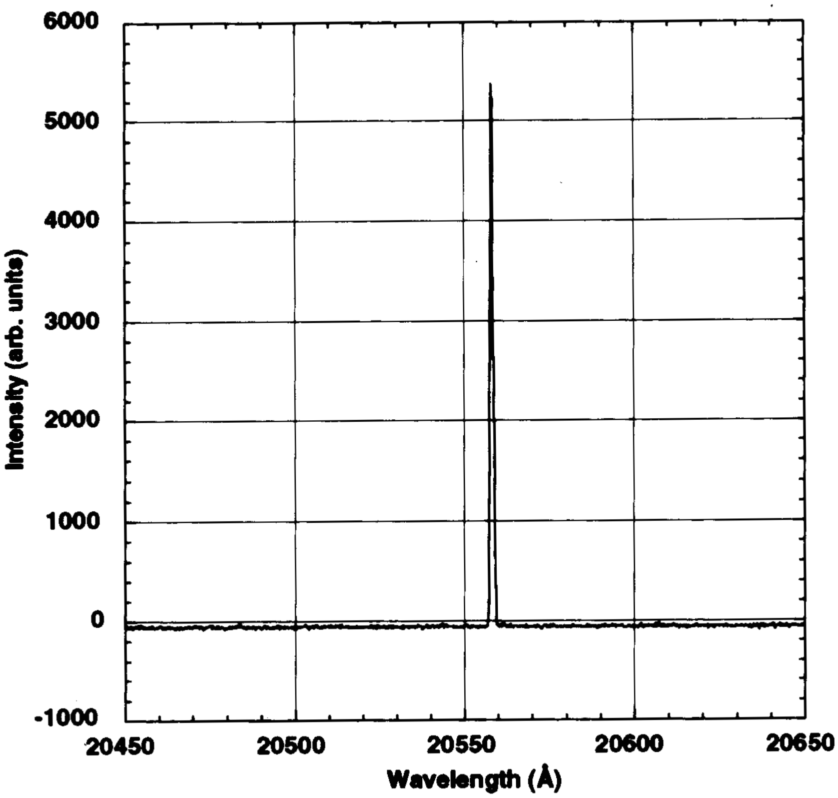


Fig. 5. Longitudinal mode spectra of the InGaAs/InP strained quantum well distributed feedback laser with emission wavelength at ~2.055 μm at room temperature.

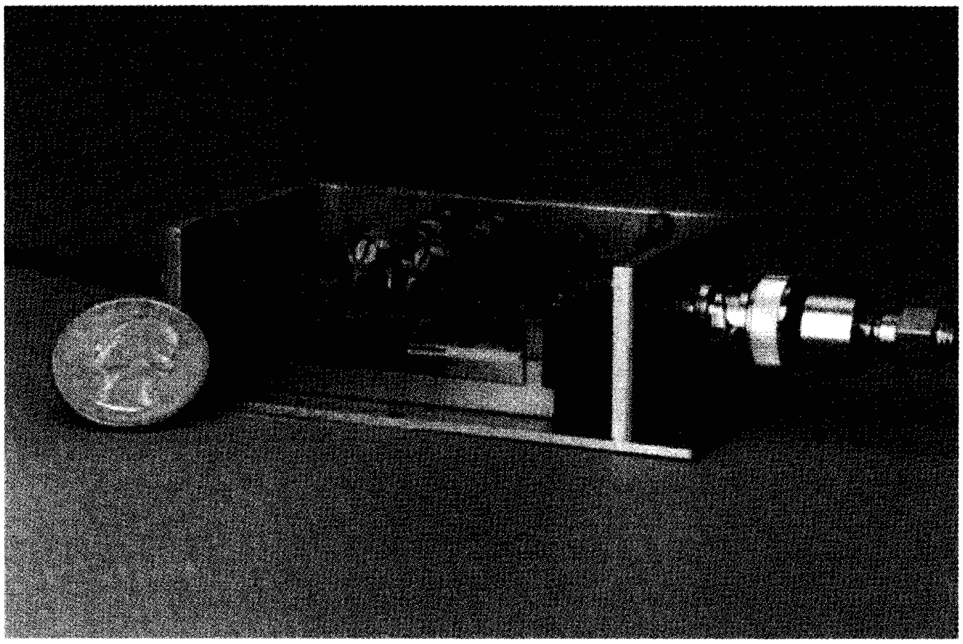


Fig. 6. JPL microseismometer prototype with silicon suspension.

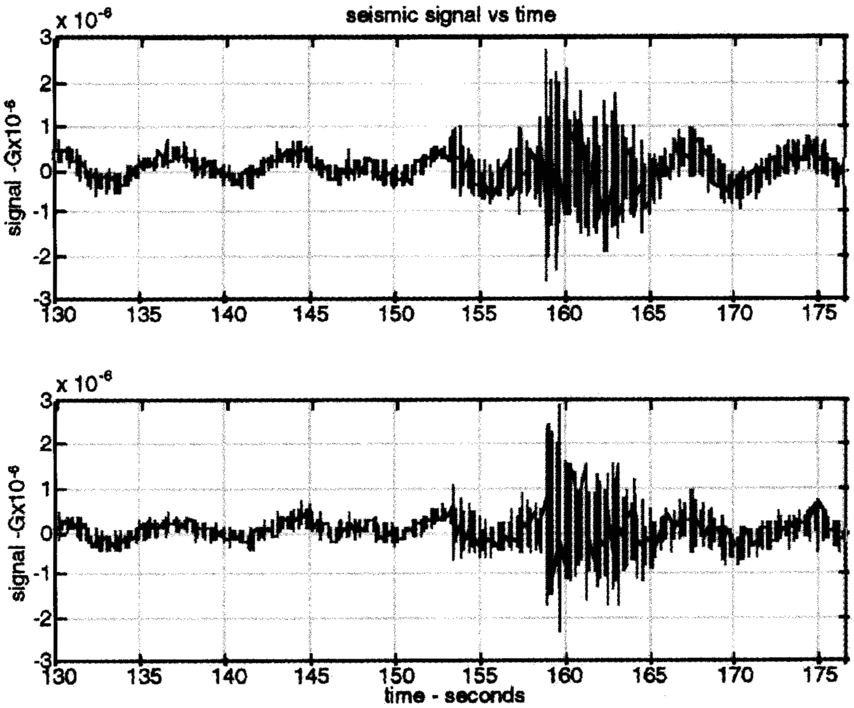


Fig. 7. Comparison of seismic data recorded by a conventional seismometer STS-2 (top) and micro-seismometer (bottom).

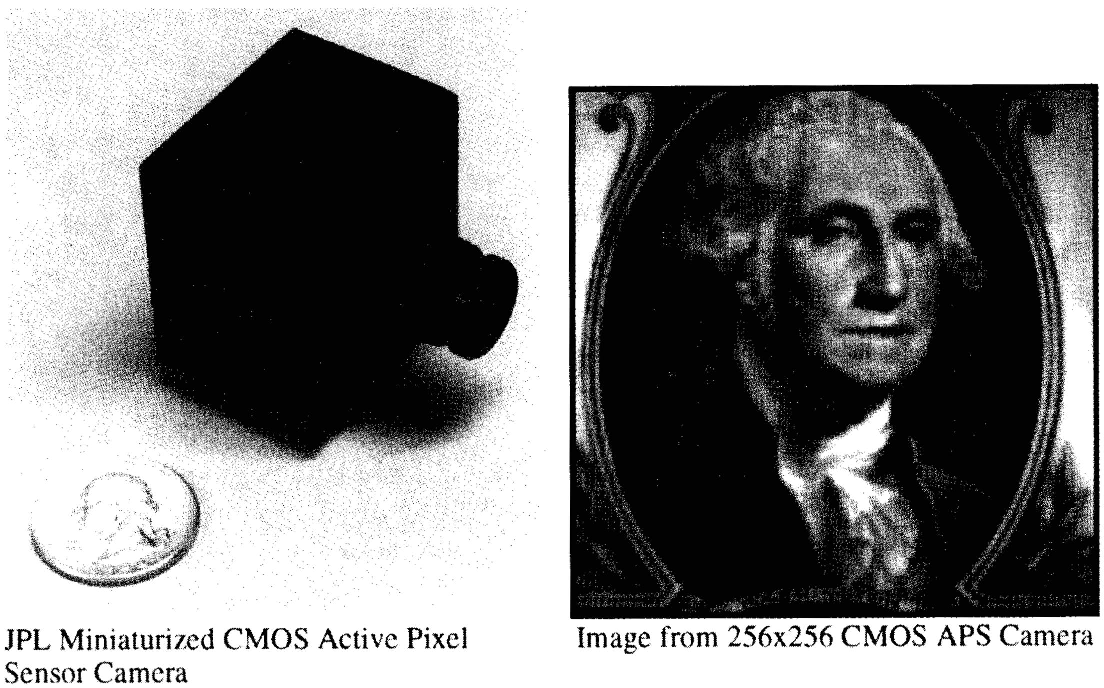


Fig. 8. (a) JPL miniaturized CMOS active pixel sensor camera. (b) Image from 256×256 CMOS APS camera.

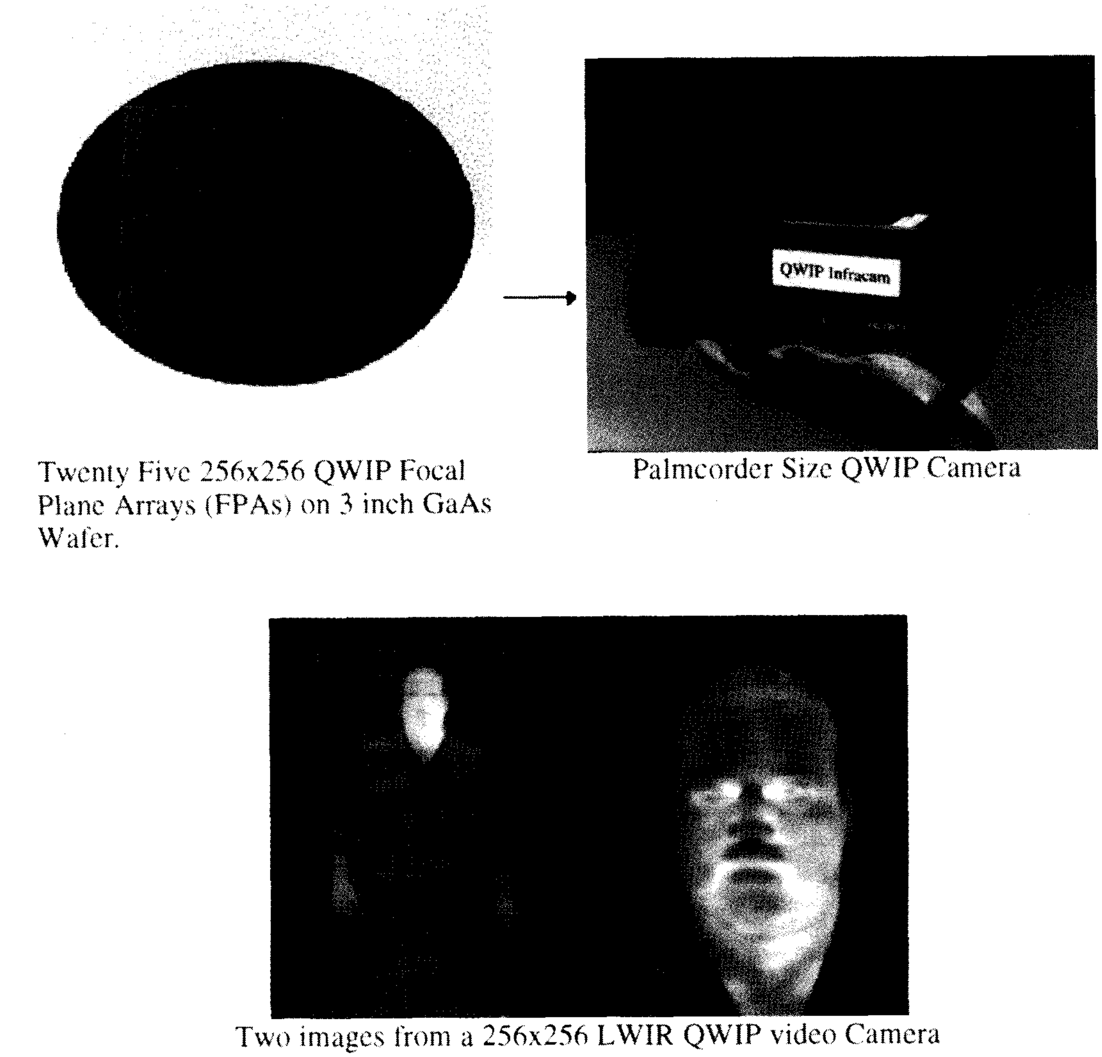


Fig. 9. (a) Twenty-five 256×256 QWIP focal plane arrays (FPAs) on a 3 inch GaAs wafer. (b) Palmcorder size QWIP camera. (c) Two images from a 256×256 LWIR QWIP video camera.

aperture or optical path, strong electric or magnetic fields, a large proof mass, a cryocooler, or sophisticated sample handling.

In many cases, the miniaturized sensor or instrument will have less sensitivity than its larger counterpart. For example, an optical sensor will collect less light with a smaller aperture. To compensate, a more sensitive detector may be needed or the instrument will have to be used in a new way. A sensitive seismometer usually has a weak spring and a heavy proof mass which leads to a large motion of the proof mass which is the measured quantity. A small seismometer has a stiff spring and a light proof mass. This yields only small excursions of the proof mass which are more difficult to measure. New techniques have been developed to overcome this obstacle. The new techniques in general can also be applied to large systems to further improve their sensitivity, but these techniques might not have been discovered at all if they were not needed for miniaturization.

Unique NASA measurement requirements and the unusual environment on planetary surfaces present new challenges to scientific measurements. Who else needs a microseismometer with 10^{-11} g/$\sqrt{\text{Hz}}$ sensitivity than can withstand a hard landing on Mars and operate in an external environment where the temperature is 200 K? Venus is the opposite extreme where a runaway greenhouse effect keeps the surface temperature at 850 K.

MICROSENSORS AND MICROINSTRUMENTS

Infrared lasers that emit a single wavelength of light can be tuned to a specific absorption line of gases such as water vapor (H_2O), or carbon dioxide (CO_2) to perform *in situ* monitoring of trace gases with sensitivities in the parts-per-billion range. In the past, lead salt lasers were used in these atmos-

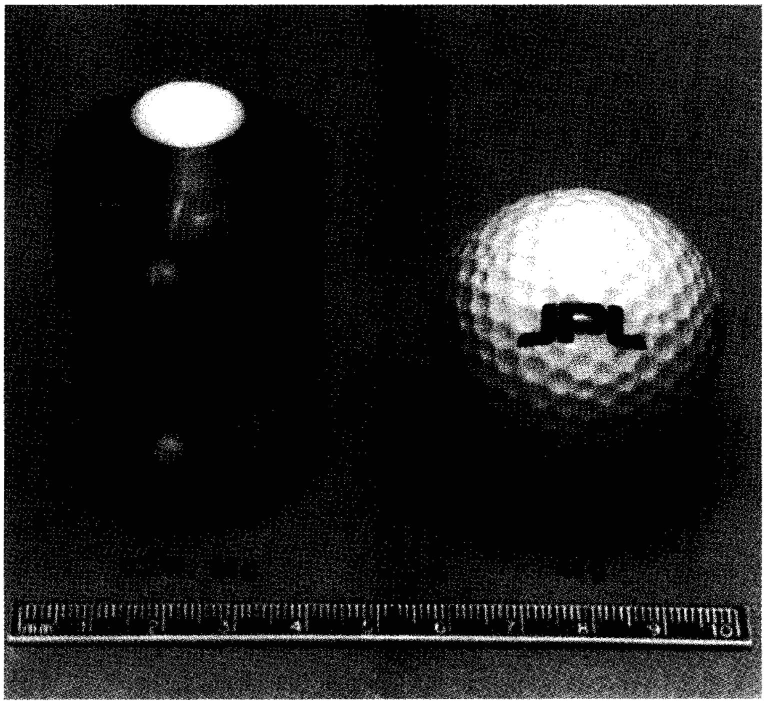


Fig. 10. Miniature nuclear magnetic resonance system.

pheric monitoring applications. These lasers had to be cooled often to liquid nitrogen temperatures. This necessitated a large cryocooling system that led to an instrument with a mass of 70 kg.

Researchers at JPL's Center for Space Microelectronics Technology (CSMT) have perfected an uncooled tunable diode laser based on indium gallium arsenide phosphide (InGaAsP) multiquantum wells grown by metal organic chemical vapor deposition with an integrated grating structure defined by electron beam lithography (Fig. 3). InGaAsP lasers in the 1.3–2.1 micron wavelength

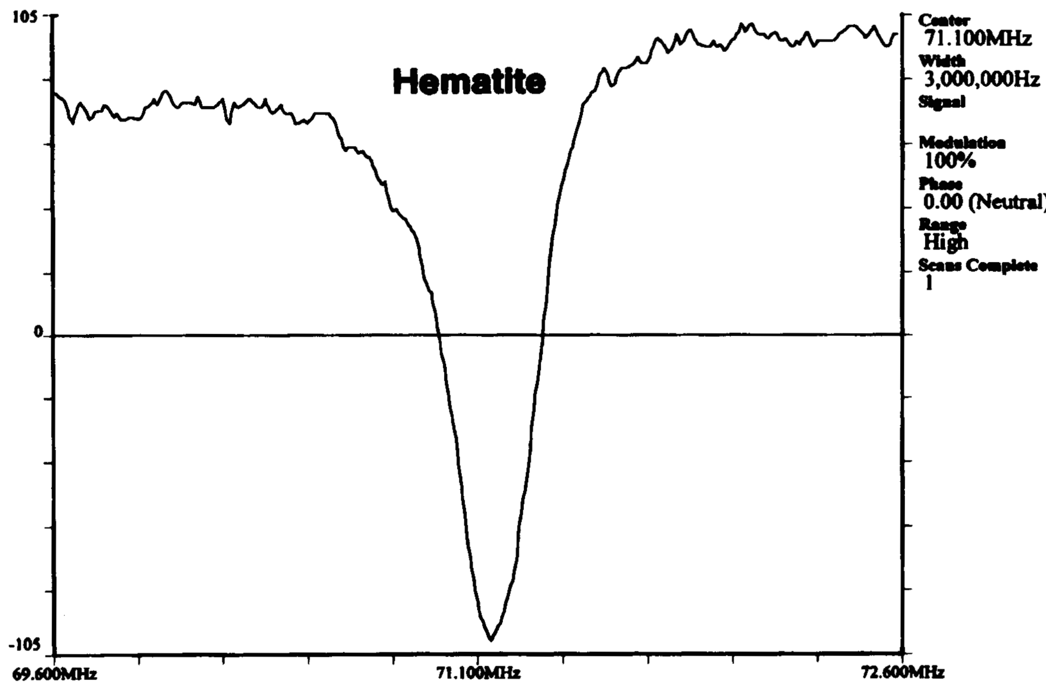
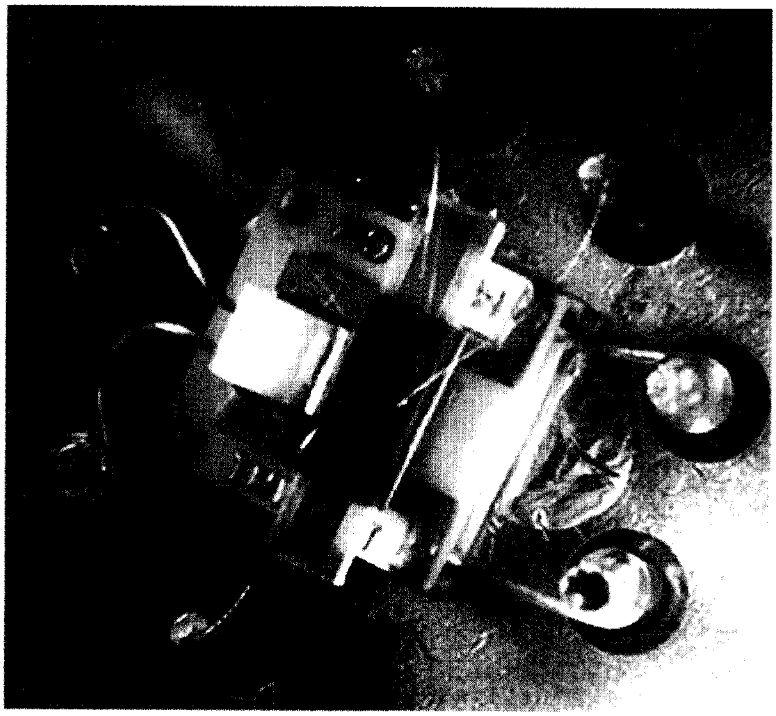


Fig. 11. Actual NMR spectra from Hermatite sample as scanned using the spectrometer instrument.



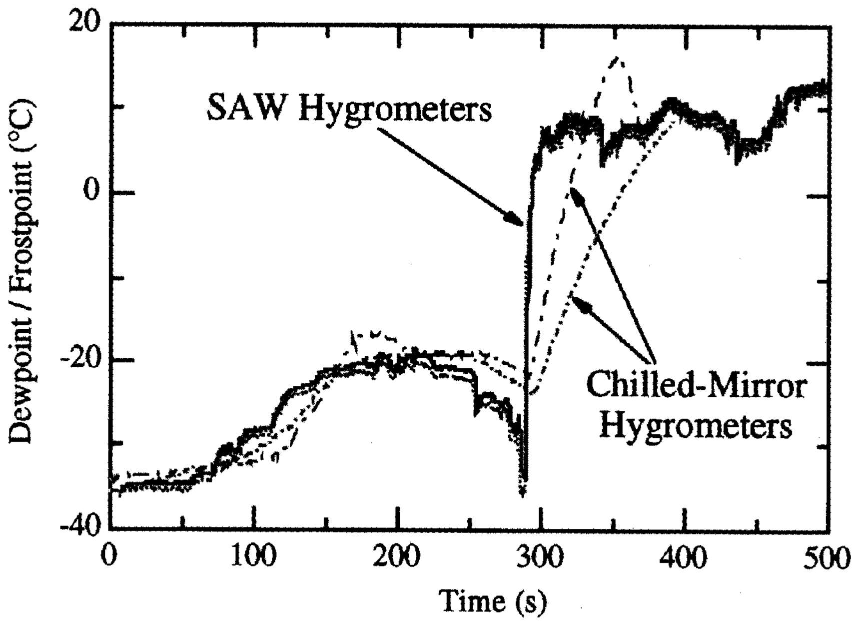


Fig. 12. (a) Close-up of moisture sensor used in the microhygrometer. (b) Humidity data taken during descent of the DC-8 Airborne Laboratory on May 19, 1995. The two SAW microhygrometers respond far faster than the two chilled-mirror hygrometers, with correspondingly higher accuracy in dynamic conditions.

region offer order of magnitude higher output powers improved spatial beam characteristics in addition to ambient temperature operation compared to their lead salt predecessors (Figs 4 and 5).

Microinstruments based on InGaAsP TDL's will be landed on Mars in 1999 to measure water vapor in the Martian atmosphere, and subsurface Mars soil samples gathered by the New Millennium micropenetrator will be heated to measure the water content stored in the Martian soil.

Seismometry has been identified as a technique for studying the internal structure of solid planets, comets and asteroids. Detection of a Marsquake may reveal that Mars has a liquid core like the Earth. Sensitive seismometers that measure earthquakes are well developed, but are delicate instruments that operate in highly temperature-controlled environments. CSMT technologists have developed a miniature and robust seismometer that utilizes a new sensitive switched capacitor transducer to measure the small motion of the proof mass (Figs 6 and 7). The microseismometer has been selected to fly on the European Space Agency ROSETTA mission to land on a comet.

Most future planetary surface missions will face serious power constraints and the visible imaging system based on a CCD camera is a significant power drain. JPL has developed the active pixel sensor (APS) that uses 100× less power than a CCD (Fig. 8). Because the active pixel sensor is based on the same complementary metal oxide semiconductor (CMOS) technology used in nearly all modern electronics, the APS can be manufactured in any commercial electronics foundry. (A CCD requires a special high purity silicon production facility.) Therefore, the APS can be integrated with its timing and control circuits and an analog to digital converter to make an entire camera on a chip. The sensitivity of the APS is equal to all but the lowest noise CCDs and is suitable for many ultra-low power, highly miniaturized imaging cameras for space and commercial applications. As a matter of fact the commercial applications of the APS are enormous and Eric Fossum, the inventor, has left JPL to form his own company, Photobit. Active pixel sensors have been demonstrated in 256×256 and 1024×1024 pixel formats.

CSMT has developed large format (256×256 and 480×640 pixel) long-wavelength infrared detector arrays that have been incorporated in miniature portable cameras. The gallium arsenide based quantum well infrared photodetector (QWIP) can be designed to be responsive in a narrow 1 μm band anywhere in the range from 6 to 21 μm.

A 9 μm 256×256 JPL QWIP detector has been incorporated into portable cameras by both Amber and Inframetrics (Fig. 9). The Infracam is the size of an 8 mm camcorder with a mass of 1 kg. It incorporates a miniature stirling refrigerator that cools the focal plane to 70 K. The QWIP camera can detect temperature changes of 30–50 mK. The Infracam is powered by a camcorder battery that yields an operating life of 3 h before recharging is needed.

Other center microsensor activities include a miniature nuclear magnetic resonance instrument (Figs 10 and 11), microweather station components including a dewpoint hygrometer (Fig. 12), a microlaser doppler anemometer, micromagnetometer, and a computed tomography imaging spectrometer.

These microsensors and microinstruments are being currently developed as independent packages. In the future, scientists, technologists and engineers will join in interdisciplinary teams to produce integrated sciencecraft including orbiters, landers, penetrators and rovers.

For more information see the Center for Space Microelectronics Technology website: http://csmt.jpl.nasa.gov.

Acknowledgements—The research described in this paper was performed by the Center for Space Microelectronics Technology, Jet Propulsion laboratory, California Institute of Technology, and was sponsored by the National Aeronautics and Space Administration, Office of Space Science and the Ballistic Missile Defense Organization.